PAPER AAS 93-567

DESIGN OF THE GALILEO SATELLITE TOUR

Aron A. Wolf and Dennis V. Byrnes

Jet Propulsion laboratory
California Institute of Technology
Pasadena, California

AAS/AIAA Astrodynamics Specialist Conference

VICTORIA, B. C., CANADA AUGUST 16-19, 1993

AAS Publications Office, P. O. Box 28130, San Diego, CA 92198

AAS 93-567

DESIGN OF THE GALILEO SATELLITE TOUR

A. A. Wolf* and D. V. Byrnes**

In May of 1992, a satellite tour trajectory for the Galileo mission was chosen from a set of candidate tours. The design of these candidate tours and the selection of the tour described in this paper were the result of an intensive 8-month effort. Concepts, strategies, and techniques developed in the 1970s and 1980s, which were used in designing the satellite tour for the 1986 launch opportunity (prior to the Challenger accident), were employed and extended for this effort. Some new techniques had to be developed during the course of this effort to respond to changes in mission constraints and science priorities made since the Galileo spacecraft was launched in 1989.

INTRODUCTION

The Galileo mission is the first mission to use an atmospheric probe and an orbiting spacecraft to perform an intensive investigation of Jupiter, its environment, and its Galilean satellites (Io, Europa, Ganymede, and Callisto). See references 1 and 2 for overall descriptions of the mission. Prior to arrival at Jupiter, the atmospheric probe separates from the larger portion of the spacecraft, which serves as a Jupiter orbiter. After its insertion into orbit about Jupiter, the Galileo orbiter travels in a series of highly elliptical orbits about Jupiter. This series of orbits is referred to as the "satellite tour". The tour contains ten close "targeted" flybys of the Galilean satellites. A targeted flyby is one where the orbiter's trajectory has been designed to pass through a specified aimpoint (latitude, longitude, and altitude) at closest approach in order to use the satellite's gravitational influence to produce a desired change in the trajectory. Pre-launch estimates of propellant and other consumable resources set the number of targeted flybys in the nominal tour.

Targeted flybys are capable of making large changes in the orbiter's trajectory. Each targeted flyby is used to target the orbiter to the next flyby. At each satellite encounter, different aimpoints exist that allow the orbiter to return to the same satellite, or to target to a different satellite. The abundance of aimpoints at each satellite encounter makes possible a large number of possible tours, each of which may satisfy many of the science objectives in different ways. While it is possible to design a tour to satisfy any single science requirement, it is difficult to design a single tour which com-

* Member of Technical Staff, Jet Propulsion Laboratory, California Institute of Technology

** Member of Technical Staff, Jet Propulsion Laboratory, California Institute of Technology, Member MS, Member AIM

pletely fulfills all the science requirements, because the trajectories needed to satisfy different science requirements tend to be dissimilar.

Tour design involves maximizing science return in competing science areas while satisfying mission-imposed constraints. Multiple science objectives must be accomplished at each flyby and on each orbit to maximize science return. The strategies used to achieve high science return while meeting constraints are examined here. Particular attention is paid to methods used to meet changes in science priorities and constraints which have been made since launch. The final tour selected by the Galileo project is presented.

SCIENCE OBJECTIVES

The scientific investigations to be performed by the orbiter can be divided into three areas: investigations of Jupiter and its atmosphere, the fields and particles in Jupiter's magnetosphere, and the Galilean satellites. Galileo science requirements have previously been discussed in detail (references 3,4). A brief review is presented here.

Atmospheric Science

Observations of cloud features and other dynamics in the Jovian atmosphere can only be made of sunlit portions of Jupiter and are best done at great distances in order to view the planet with the narrow angle camera. Other atmospheric phenomena of interest, such as lightning, are best examined as the orbiter passes over Jupiter's unlit side.

Magnetospheric Science

The most important magnetospheric science requirements are to pass through the Jovian magnetotail at a distance of at least 150 RJ (Jupiter radii), and to pass through the wake and Alfven wing regions surrounding each satellite. The magnetotail streams out from Jupiter in a shape roughly resembling a windsock in the direction opposite the sun. The region of greatest scientific interest lies within 15 deg. either side of the anti-sun line. Satellite "wakes" are created as charged particles trapped in Jupiter's magnetic field sweep by the satellites. Jupiter's magnetic field rotates with Jupiter at a rate faster than the rotation rates of the satellites around Jupiter. Therefore, the wakes stream out in front of each satellite. Wake passes are achieved with flybys near a satellite's equator over the satellite's leading edge. Such flybys reduce orbital period (see also the brief discussion of gravitational assist below). An "Alfven wing" is a wave generated in Jupiter's magnetic field by plasma moving by a satellite, This wave propagates in a region located approximately over a satellite's poles, tilted toward the direction of motion of the satellite. Passages through Alfven wing regions are achieved by flying nearly over a satellite's pole. Such flybys change inclination but do not appreciably change period.

Satellite Imaging

The goal given the highest priority in satellite imaging is to maximize the number of high-resolution images obtained with the SSI (Solid State Imaging) camera. Coverage at high resolutions can only be obtained at low altitudes during targeted flybys when passing over the lit side of a satellite. Because of the narrow field of view of the SSI instrument and the small number of flybys, it is possible to image only a small portion of each satellite at high resolution.

Much larger portions of the satellites can be imaged at lower resolutions. Maximizing the area covered at SSI resolutions of 1 km or better is a high priority goal. These resolutions are obtained at altitudes of 50,000 km or less, which are achieved along the approach and departure asymptotes of targeted flybys. of equal importance is NIMS (Near Infrared Mapping Spectrometer) coverage at 25 km resolution or better under high-sun conditions (i.e. when the sun-viewed surface-orbiter angle is 60 deg. or less and the sun-surface-zenith angle is 50 deg. or less). The NIMS instrument measures the spectrum of sunlight reflected from the surface in order to determine satellite composition. Because of the lower resolving capability of the NIMS instrument, the distance at which NIMS coverage is obtained at 25 km resolution is the same al which SS1 coverage is obtained at 1 km resolution).

Each of the Galilean satellites is in synchronous rotation with Jupiter; that is, the same satellite hemisphere always points toward the planet. Therefore, changes to the shape, size, and orientation of the orbiter's orbit do not appreciably change the "real estate" viewed along the approach or departure asymptotes to a flyby (see Figure 1). Approaching an outbound flyby (one occurring after perijove), the region near O deg. longitude (facing Jupiter) is visible, and the region near 180 deg. longitude (facing away from Jupiter) is visible when departing. The reverse is true for an inbound (pre-perijove) flyby: the region near 180 deg. longitude is visible along the approach asymptote, and the region near O deg. longitude is visible from the departure asymptote. Coverage of both hemispheres of a satellite requires at least two separate encounters, one inbound and one outbound.

The areas visible near closest approach lie near the 90 or 270 deg. longitude regions, depending on whether the orbiter passes over the leading or trailing edge of the satellite. Small portions of these regions are covered at high resolutions during targeted flybys, but most of the area in these longitude regions cannot be covered during targeted flybys because. these areas cannot be seen from the asymptotes. This give.s rise to gaps in coverage near the 90 and 270 deg. longitude regions. which unfortunately coincide with regions not observed hy the Voyager spacecraft. Both the Voyager and Galileo trajectories are posigrade, with perijoves far beneath the orbits of Ganymede and Callisto.

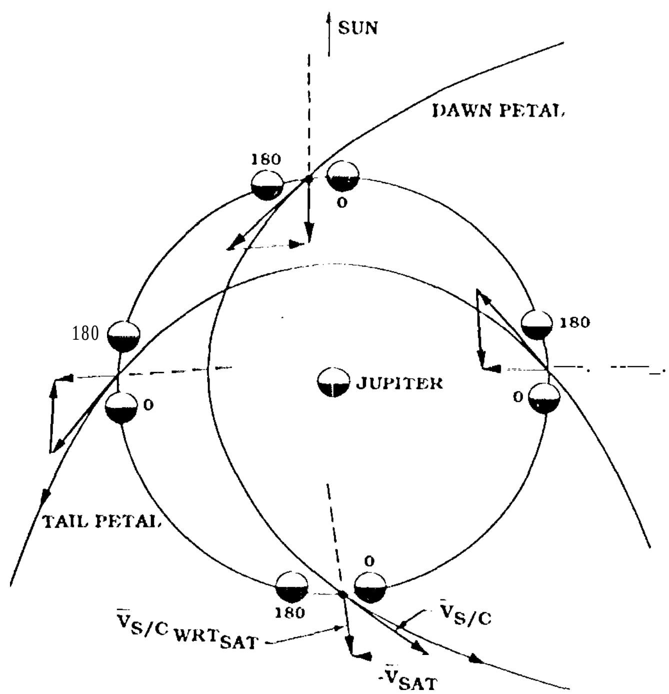

Figure 1

It is possible to fill the coverage gaps by designing satellite flybys whose Closest approach altitudes are on the order of tens of thousands of km. At a closest approach altitude of 50,000 km or less, the entire region near 90 or 270 deg. longitude can be imaged at 1 km SSI resolution; at 100,000 km or less, the region can be imaged at 2 km resolution. The effect of such flybys on the orbiter's trajectory is small, due to the much greater distance at Which the flyby occurs. These distant flybys are called "nontargeted" flybys, because their flyby aimpoints need not be tightly controlled, as is the case for targeted flybys. Coverage of the regions near both 90 and 270 deg. longitudes of a satellite requires two separate encounters, one inbound and one outbound. Nontargeted flybys provide excellent opportunities to fulfill science requirements for global imaging of satellites. For this reason, candidate tours should include as many nontargeted flybys as possible.

Coverage of Europa was assigned the highest priority by the science teams, followed by coverage of Ganymede, then Callisto. Particular interest was expressed by science teams in tours containing two nontargeted flybys of Europa. A consensus emerged that a tour With two Europa nontargeted flybys and a nontargeted flyby Of either Ganymede or Callisto would be acceptable.

Radio Science

Radio science experiments support all three major science areas (magnetospheres, atmospheres, and satellites). When the orbiter passes behind Jupiter as viewed from Earth, radio signals from the orbiter are not cut off. Instead, they are refracted by the dense Jovian atmosphere on their way to Earth. Polarized radio signals are also influenced by the magnetic field of Jupiter, through a phenomenon called the Faraday effect, Because a great deal of information on the atmosphere and magnetic field may be gleaned by analysis of the refracted polarized signals, passes behind Jupiter are desired in the tour. Such passes are called occultations of Earth by Jupiter, as viewed from the orbiter. Occultations of the sun by Jupiter as viewed from the orbiter [i.e. passages through Jupiter's shadow) are also desired, because they offer an opportunity to observe lightning and other atmospheric phenomena best seen in the dark.

For tours associated with arrivals at Jupiter in 1995, Jupiter's equator is viewed nearly edge-on from Earth; thus, occultations of Earth by Jupiter as viewed from the orbiter are achieved on many orbits without the use of flybys 10 change orbital inclination.

Occultations of Earth by the Galilean satellites as viewed from the orbiter are also desired in the tour, in particular by Io, where the radio signal may be distorted due to outgassing from volcanic plumes. However, radiation considerations prohibit the orbiter from approaching Io more than once, and no occultation occurs during the single Io flyby on the insertion orbit. Therefore, tour design efforts have included attempts to incorporate occultations of Io at greater distances in other portions of the tour. Opportunities to obtain such "distant Io occultations" frequently exist during orbits containing near-equatorial occultations Of Earth by Jupiter. Orbital inclination must be tightly controlled to be assured of passing behind a small satellite at a large distance. It is necessary to use the targeted flyby immediately preceding a distant satellite occultation to change inclination to the precise value needed to achieve the occultation.

TOUR DESIGN CONCEPTS

During the tour, the gravitational fields of the satellites are used to make large alterations in the trajectory. The concept of gravitational assist has been extensively discussed previously (references 2-8) and employed in previous missions. Briefly explained, a satellite flyby can change the direction, but not the magnitude, of the orbiter's velocity relative to the satellite. This change in the direction of the *satellite-relative* velocity vector can change both the direction and the magnitude of the orbiter's velocity vector *relative to the central body* (Jupiter, in the case of the Galileo tour).

Flybys can be used to change energy with respect to the. central body, equivalent to changing orbital period. For tours like that of Galileo in which the plane of the orbiter's orbit lies near the planes of the satellites' orbits, this is done by flying over the satellite at or near its equator. increasing orbital period [referred to as "pumping up") with respect to the central body is accomplished by flying behind a satellite's trailing edge. Decreasing orbital period ("pumping down") "involves flying ahead of its leading edge.

Flybys can also be used to change the orbit without changing orbital period. This technique is referred to as "orbit cranking". For tours in which the orbiter's orbit lies near the planes of the satellites' orbits, this is tantamount to changing inclination, and is done by flying over one of the satellite's poles. Flying over a satellite at latitudes between the equator and a pole produces a change in both period and inclination.

Flybys which change orbital period also rotate the line of apsides and change the distance of perijove from Jupiter. For a given period change, a flyby which occurs far from the orbiter's perijove rotates the line of apsides and changes perijove distance more than a flyby occurring close to perijove. A flyby occurring exactly at perijove changes orbital period without rotating the line of apsides and without changing perijove distance. For example, a Callisto flyby which changes period a given amount rotates the line of apsides more than a Europa flyby Changing period by the same amount, because the orbiter encounters Callisto at a greater distance from Jupiter (hence, at a greater true anomaly). The direction in which the line of apsides is rotated depends on whether the period is increased or decreased and whether the satellite flyby occurs before perijove ("inbound") or after perijove ("outbound"). Figure 2 shows that an outbound, period-reducing flyby (from orbit A to orbit B) rotates the. line of apsides clockwise, and an outbound period-increasing flyby (from orbit B to orbit A) rotates the line counter-clockwise. Rules for orbit rotation are listed in Table 1.

The angle measured clockwise at Jupiter from the Jupiter-sun line to the apojove, referred to as the "orbit orientation", is an important consideration for atmospheric observations. The time available for observations of Jupiter's lit side decreases as the orbit rotates toward the anti-sun direction. Arrival conditions at Jupiter fix the initial orientation at about 125 deg. Due to the motion of Jupiter around the sun, the orbit orientation increases with time, at a rate of 2.52 deg. /month. Over the 23-month nominal duration of the tour, the total amount of drift in orbit orientation is 58.0 deg. This means that the orbit orientation at the end of the tour would be about 183 deg. (that is, within 3 deg. of the anti-sun direction) if changes in orbit orientation were due only to orbit drift. Period-changing targeted flybys which rotate the line of apsides may be used to add to or subtract from this drift in orbit orientation. The rotation of the orbit from the initial orientation to the anti-sun direction for the tour presented here is shown in Figure 3, referred to as a "petal plot" because of the resemblance of the orbits to the petals of a flower. In the coordinate system used in this figure, the direction to the sun is fixed.

CONSTRAINTS

Tour design is constrained by many factors, several of which are unrelated to the laws of orbital mechanics. Constraints are imposed due to the limits of hardware capabilities, instrument reliability, navigational accuracy, and budgetary concerns.

The arrival conditions at Jupiter are fixed by the interplanetary trajectory. The orbiter arrives at Jupiter on Dec. 7, 1995, and a propulsive maneuver is executed to in-

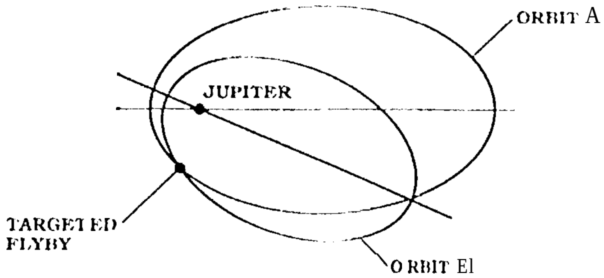

Figure 2 Apsidal Rotation Due to Satellite Flyby

Table 1
ORBIT ROTATION RULES

Flyby location	Energy (period) increasing flyby	Energy (period) decreasing flyby
Inbound (pre-perijove)	Clockwise	Counterclockwise
Outbound (post-perijove)	Counterclockwise	clockwise

Note: Clockwise rotation is in the direction from the initial orbit orientation (near the dawn terminator of Jupiter) toward the anti-sun direction.

sert the orbiter into orbit about the planet. Performance considerations restrict the post-insertion orbit period to within the 200-230 day range. The insertion orbit is inclined about 6 deg. to Jupiter's equator.

A minimum time interval of 35 days between targeted flybys is required in order to allow enough time for the design of command sequences between encounters. This required interval had previously been set at 28 days, but was increased as a result of further analysis of the time required to generate command sequences for the orbiter.

The allowed duration of the tour is set by the Galileo project due to budget considerations. For the 1986 launch opportunity, the duration limit was set at 22 months from Jupiter orbit insertion. A 22-month duration constraint is difficult to meet even with as little as 28 days allowed between flybys. The allowed duration of the tour was increased to 23 months in order to accommodate the increase in the minimum time interval allowed between targeted flybys.

A solar conjunction occurs during the tour on January 19, 1997. Reception on the orbiter of the radio signal from Earth is degraded significantly whenever the Sun-Earth-orbiter angle is less than 5 deg. The effect of this signal degradation on the uplink of command sequences is such that no close satellite flyby is allowed between January 8 and February 1.

Only a limited amount of propellant is available for tour operations. Propellant is used only to provide small adjustments to the trajectory necessary to navigate the orbiter, to turn the orbiter for science-gathering purposes or to communicate with Earth. Designing a tour which minimizes propellant use was an especially high-priority objective during this tour design effort. Because propellant was expended in attempts to free the spacecraft's stuck high-gain antenna during interplanetary cruise (reference 1), minimizing propellant use during the tour was necessary in order to be able to include a flyby of the asteroid Ida during interplanetary cruise while retaining the ability to complete ten targeted satellite flybys in the tour.

Instrument and orbiter reliability concerns impose a maximum accumulated radiation dosage value of 150 krad to which the orbiter may be exposed. Energetic electrons and protons trapped in Jupiter's radiation belts can cause interference and damage in electronic parts in the Galileo orbiter. The measure of radiation dosage adopted is the dose in krad that would penetrate shielding equivalent to 2.2 g/cm^2 of aluminum in the Jovian radiation environment. To ensure that such effects do not seriously degrade performance, the maximum acceptable radiation dose for the entire mission has been set at 150 krad.

Since Io orbits deep within the radiation belts, only one Io flyby is permitted during the mission. Io is used on the insertion orbit to slow the orbiter, which reduces the amount of ΔV needed to accomplish insertion into orbit about Jupiter. During this single Io flyby, the orbiter absorbs approximately 40-50 krad, approximately one third of the dose allowed during the entire mission. A perijove raise maneuver is performed near the first apojove which raises perijove high enough so that the 150 krad constraint is not exceeded during the remainder of the mission. Perijove must be kept near or beyond Europa's orbit during the remainder of the mission in order not to exceed the 150 krad constraint.

The requirement to navigate the orbiter accurately allows no more than one targeted and one nontargeted satellite encounter per orbit. This requirement is due to the differences expected between the predicted and the actual post-flyby orbit which accrue due to imperfect knowledge of the pre-flyby orbit, the satellite orbits, and other factors. Navigational constraints also impose a minimum satellite flyby altitude of 500 km for the first targeted flyby, 200 km for subsequent targeted flybys, and 25,000 km for nontargeted flybys.

TOUR DESIGN STRATEGY

Orbit Orientation

The petal plot of Figure 3 shows that the orbiter spends a great deal of time on Jupiter's dark side. In order to maximize the amount of time available to observe lit portions of Jupiter (which is a high priority for atmospheric science), the orientation of the orbiter's orbit must be kept close to the initial orientation for as long as possible. Consequently, targeted flybys near the beginning of the tour are designed to counteract the clockwise orbit drift (to "counter-rotate" the orbit).

If the first few flybys in the tour are used to counter-rotate for observations of Jupiter's lit side, the drift in orbit orientation due to Jupiter's motion about the sun is not sufficient by itself to reach the anti-sun direction, where the magnetotail lies, by the end of the tour. Subsequent flybys must be employed to help rotate the orbit toward the anti-sun direction in order to achieve magnetotail passage. In most previously designed tours, the magnetotail passage was placed at the end of the tour. This permits more counter-rotation at the beginning of the tour, which maximizes atmospheric observation time. The last satellite flyby is used to increase the orbital period to approximately 90 or more days in order to achieve a distance of 150 RJ at the apojove of the

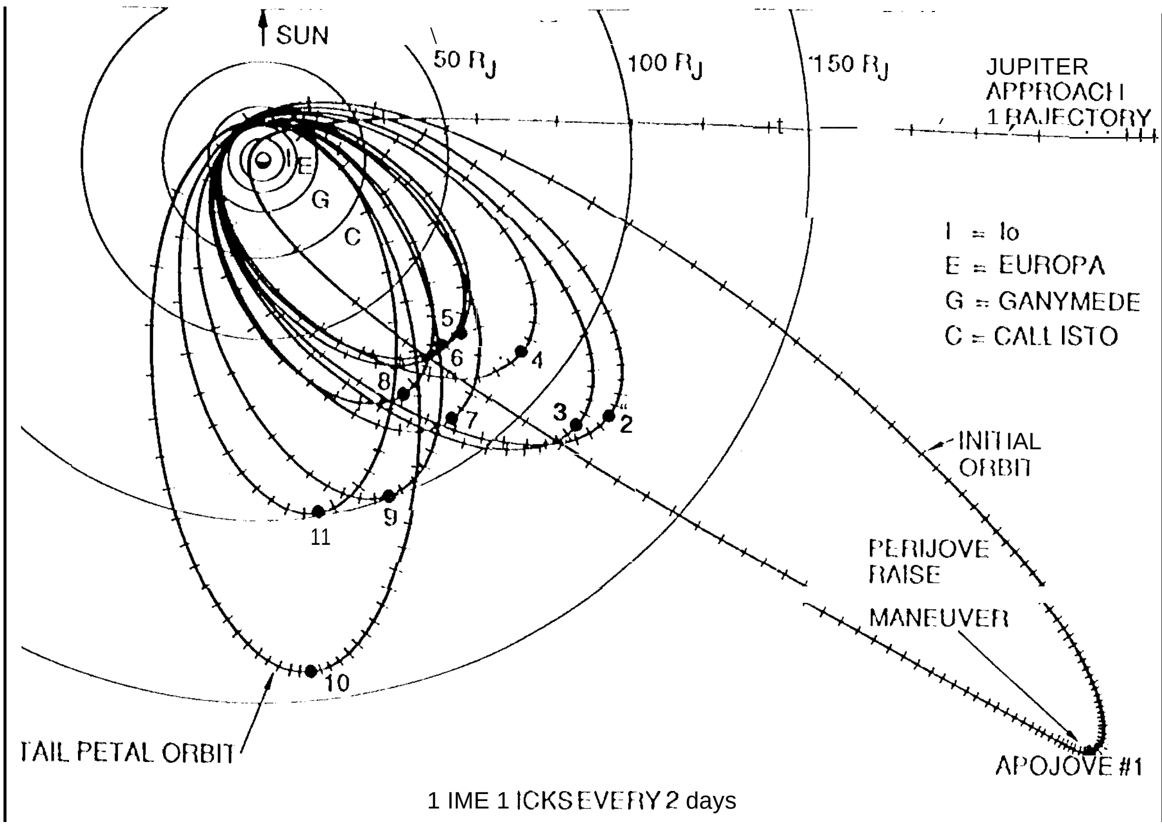

Figure 3 Tour Petal Plot

"tail petal" orbit (the orbit on which magnetotail passage is achieved). The 23-month limit on the tour's duration is satisfied if the magnetotail passage, which occurs near apojove, is completed within 23 months. Consequently, for tours in which the magnetotail passage is placed after the last targeted flyby, it is not necessary to include the post-apojove portion of the tail petal orbit [lasting approximately 45 clays) within the 23-month limit.

Prior to this final tour design effort, the Galileo Project specifically requested that some candidate tours be designed in which the magnetotail passage occurs after the eighth targeted flyby, rather than the tenth. Hating the magnetotail passage after the eighth targeted flyby rather than at the end of the tour has the effect of reducing the time available for atmospheric observations. This occurs because it is necessary to begin rotation toward the anti-sun direction earlier in the tour in order to reach the anti-sun direction earlier. Placing the magnetotail passage earlier also increases the difficulty of designing a tour which meets the 23-month duration limit with no less than 35 clays between any two targeted flybys. Because two targeted flybys remain after the magnetotail passage, the tour cannot be considered complete at the apojove of the tail petal orbit, and the period of roughly 45 days between apojove and the subsequent flyby must be included within the 23-month limit.

Alfven wing passes which do not appreciably change period must also be included in the tour, This means the tour cannot consist solely of counter-rotating flybys at the beginning followed by rotating flybys at the end: there must be a few flybys designed to produce Alfven wing passes, which provide little or no apsidal rotation (i. e., which neither rotate nor counter-rotate the orbit).

Orbital Period Profile

The 23-month duration limit, the requirement that not less than 35 days elapse between targeted flybys, and the limitations of the satellites' abilities to provide gravitational assist make it possible to specify a rough profile of desired orbital periods at various points in the tour before the tour is designed. Given the orbiter's post-insertion orbital period of 200-230 days and the tail petal orbital period of approximately 90 days, the average time interval between encounters for the remaining flybys must be approximately 48 days in order to finish the tour in 23 months. Orbital period must be reduced early in the tour, then increased to nearly 90 days for the magnetotail passage, then reduced again as quickly as possible in order to finish the tour within 23 months from arrival at Jupiter.

The targeted flyby strategy used in previous tours (references 4, 5) accomplishes the above objectives well, and was used in this tour. The first encounter, with Ganymede, is designed for maximum period reduction, and is placed inbound to perijove in order to counter-rotate the line of apsides. The second flyby, also with Ganymede, reduces inclination, aligning the orbital plane more closely with the Jovian equator in order to enable the orbiter to encounter satellites other than Ganymede. The third flyby, with Callisto, further reduces period, depressing perijove to below Europa's orbital radius to make possible a Europa flyby and further counter-rotating the apsidal line.

Nontargeted Flybys

It is, of course, desirable to include as many nontargeted flybys as possible in the tour. A "nontargeted flyby opportunity" is said to occur at any combination of orbit orientation, perijove distance, orbital period, and time for which it is possible to encounter two satellites on one orbit. The tour must be designed to arrive at the combinations of orientation, perijove distance, and period necessary to achieve nontargeted encounters in Conjunction with targeted encounters at various points in the tour. This, of course, must be accomplished within the constraints of the orbit orientation profile discussed above (which itself is a compromise between the conflicting requirements to maximize time over Jupiter's lit side and to reach the magnetotail) and the perijove profile required to manage the orbiter's exposure to radiation.

The occurrence of nontargeted flyby opportunities is tied to the synodic period of the satellite pair (reference 4). For example, opportunities involving Ganymede and Callisto are of interest, because seven complete Ganymede revolutions take almost the same amount of time as three complete Callisto revolutions (slightly more than 50 days). For a given period, perijove, and encounter sequence, the positions of the satellites with respect to each other and to Jupiter change by only approximately 2 deg. after 50 days have elapsed. This rate is slightly lower than the average desired precession rate of the orbiter's orbit toward the magnetotail. Therefore, if conditions produce a Ganymede-Callisto targeted-nontargeted pairing on one orbit, it is often possible to achieve a similar pairing on the next orbit if the orbiter's period is approximately 50 days.

Phasing Orbit

The three-week interval during which targeted flybys are prohibited due to solar conjunction occurs in January, 1997, after the first few targeted flybys have taken place. At this point in the tour, in the absence of solar conjunction, the desired time interval between encounters would be short (35-45 days). Unfortunately, the three-week interval of prohibition severely limits the tour designer's choice of flyby dates unless the time between flybys is lengthened. (It should also be noted that lengthening the time between flybys at this point in the tour makes it more difficult to meet the 23-month duration constraint.] The time between targeted flybys can be lengthened by increasing orbital period. or by keeping orbital period short and allowing the orbiter to complete more than one orbit around Jupiter between targeted flybys.

The idea of incorporating in the tour an orbit containing no targeted flyby (a "phasing Orbit") had not been considered in previous tour design efforts, principally because no constraint or requirement drove the tour design in that direction, The phasing orbit strategy allows the orbit er's period 10 be kept small even though the time interval between flybys is long, making it easier to avoid the solar conjunction region while keeping to the desired period profile at subsequent flybys. For this final tour design effort, candidate tours with and without phasing orbits were designed.

End of Tour

For tours in which the tail petal o rbit occurs after the tenth flyby, that last flyby is required to increase period for the tail passage. For tours in which the tail petal orbit is placed after the eighth flyby, there is no specific requirement which must be fulfilled at the tenth flyby. Therefore, the last flyby may be used to accomplish any science objectives not satisfied during the earlier portion of the tour.

For tours with tail petals after the eighth flyby, the end of the tour was defined to occur 5 clays after the tenth and last targeted flyby.

TOUR OPTIMIZATION

The first step in designing a tour involves the use of conic software to fine] a tour that incorporat es the desired characteristics. The conic tour trajectory is then used as a "first g uess" in an optimization program. This program minimizes spacecraft propellant consumption subject to constraints using the method described in reference 9. This method uses a multi-conic trajectory propagation scheme to generate a tour trajectory of nearly numerical integrated accuracy. The total amount of propellant expended in deterministic maneuvers required by the spacecraft while meeting the various flyby constraints is minimized.

Experience with optimizing many candidat e tours over many years fOr the Galileo mission has resulted in a general understanding of what changes may occur between the conic anti multi-conic versions of a tour. In general there arc three areas that Snow particular sensitivity in tou r optimization. Encounters with Europa are generally sensitive since the perijove distance is just slightly less than the orbital radius of Europa. l-his means that since the spacecraft orbit anti the orbit of Europa are nearly tangent at encounter, small cha nges prior to the encou nter will have large conse - quences at the encounter. The second area of great sensitivity involves resonant orbits. A leg of the tour that involves successive encounters with the same satellite for which the! time! between encounters is an integral multiple of the satellite period is a resonant orbit. Since these two e ncounters are very nearly 360 deg. apart, the inclination of the orbit is almost indet erminate. The third area of sensitivity involves nontargeted fly - bys. Nontargeted flybys are often separated from targeted flybys by relatively short time intervals (a few days). Consequently, nontargeted flyby distances can be very sensitive to small changes in targeted flyby aimpoints. Care must be taken during the initial trajectory design and during the optimization process so that excessive AV cost is not incurred in constraining nontargeted flyby distances within the desired limits. The Subtle interplay of these sensitivities is very important in determining the final optimal tour.

An example of this interplay occurs on the eighth and ninth orbits of the tour presented here. The nontargeted flyby of Callisto on orbit 8 and the targeted flyby of Callisto on orbit 9 are nearly 360 deg. apart, as are the targeted flyby of Ganymede on orbit 8 and the nontargeted flyby of Ganymede on orbit 9. This "double resonance" creates sensitivities due to the near-360 deg. transfers which increase the difficulty of keeping the nontargeted flyby attitudes within the desired limits.

RESULTS

The goal of the tour design process is to find a tour which achieves the maximum possible science return in the three major areas (atmospheres, satellites, and fields and particles), has acceptably low propellant consumption, and does not violate mission constraints. The tour selected by the Galileo Project Science Group and presented here accomplishes this objective. A brief summary of the tour, showing the sequence of encounters and some objectives accomplished at each encounter, is presented in "1'able 2. In this table, encounters arc numbered according to the orbit on which they occur. Nontargeted encounters are designated with an "A" (e.g., Europa 3A). According to the orbit numbering convention used, the orbit number changes at apoapsis, with orbit 1 beginning at tile perijove raise maneuver.

Four nontargeted flybys are achieved in the tour. The high-priority objective of achieving two nontargeted flybys of Europa (one covering each hemisphere) is satisfied, One nontargeted flyby of Europa is achieved on orbit 3 in conjunction With a Callisto targeted flyby, and the other is achieved on orbit 6 in conjunction with a Ganymede targeted flyby. The 50-day Ganymede - Callisto resonance is used to advantage on orbits 8 and 9, which provide one nontargeted flyby of Ganymede and one of Callisto.

Table 2
GALILEO SATELLITE TOUR

Encounter	Date	Satellite	Inbound/ Outbound	Altitude (km)	Latitude (deg)	Objective
G1	4 Jul 96	Ganymede	In	500	25	Wake, Alfven wing, UVS, gravity, reduce period
G2	6 Sep 96	Ganymede	In	200	85	Alfven wing, gravity, reduce inclination
C3	4 Nov 96	Callisto	In	1096	14	Wake, Alfven wing, UVS cmunler-relate for atmospheric coverage, Jupiter occultations (Sun, Earth)
E3A	6 Nov 96	Europa	out	31818	0	Coverage (232 deg W. Long, phase . 34 deg)
E4	19 Dec 96	Europa	Out	695	0	Wake, Europa occultations (Sun, Earth), Jupiter occultations (Sun, Earth)
(E 5A)	20 Jan 97	Europa	Out	27555	-1	Occurs during solar conjunction interval on phasing orbit
E6	20 Feb 97	Europa	In	589	.17	Europa occultations (Sun, Earth), Jupiter occultations (Sun, Earth), 10 occultation
E7A	4 Apr 97	Europa	In	24993	2	Coverage (133 deg W. Long., phase = 52 deg), distant wake
G7	5 Apr 97	Ganymede	Out	3105	55	Alfven wing
C8A	6 May 97	Callisto	In	33176	-42	Coverage (72 deg W. Long phase = 43 deg)
G8	7 May 97	Ganymede	In	1602	28	Ganymede occultations (Sun, Earth), Jupiter occultations (Earth), distant UVS
C9	25 Jun 97	Callisto	In	420	2	Callisto occultations (Sun, Earth), Jupiter occultations (Earth), Io occultations, tail petal
G9A	26 Jun 97	Ganymede	In	80246	0	Coverage (98 deg W. long., phase = 20 deg), distant wake
Tail Petal Apojove	8 Aug 97					143 R_J, 175 deg phase, 0,2 deg inclin alien
Clo	17 Sep 97	Callisto	In	528	5	Wake, Alfven wing, Jupiter occultations (Sun, Earth), rotate, UVS, reduce period
E11	6 Nov 97	Europa	In	1127	66	Alfven wing

Deterministic ΔV: Jupiter Orbit Insertion = 645 m/s, Perijove Raise = 375 m/s, Tour .23 m/s

Total Radiation .123 krad

This tour uses a phasing orbit to satisfy the solar conjunction constraint. 'he use of a phasing orbit (orbit 5 in the chosen tour) has the slight disadvantage of complicating tour nomenclature. Encounters are numbered according to the orbit during which they occur. This means, for example, that the fifth targeted flyby is referred to as Europa 6 since it takes place during the sixth orbit.

The phasing orbit contains some opportunities for additional scientific observations. The lit side of Jupiter is visible near perijove, ant] there is a nontargeted flyby of Europa which occurs on this orbit due to the near-commensurability of the orbiter's period with that of Europa. However, both perijove passage and the Europa nontargeted flyby occur during the three-week interval during which communication with the orbiter is not assured. For this reason, it was assumed for the purpose of tour evaluation and selection that no science observations are possible during the phasing orbit. The primary concern during the solar conjunction interval is maintaining the orbiter's health until communications are once again possible. However, it may be possible to tape record some science observations for later playback, depending on the tape recorder capacity and the amount of memory available in the orbiter's computers after storing other necessary commands.

The tail petal orbit is placed after the eighth targeted flyby (Callisto 9). 1-his tour allows about 26 days for observations of Jupiter's lit side, about 4 days less than tours with the tail petal orbit placed after the last targeted flyby. This slight reduction results from the need to rotate the orbit more quickly toward the anti-sun direction to facilitate the early magnetotail passage. (The 26 clay total dots not include an extra 2.4 days of observation available near the perijove of the phasing orbit during which the orbiter is out of communication with Earth.)

Only 23 m/s of deterministic AV is needed to fly the nominal trajectory. 'This is the lowest deterministic AV for any tour ever designed containing this many nontargeted flybys.

The tour contains seven occultations of Earth by Jupiter as viewed from the orbiter in addition to the one obtained on the insertion orbit, These occultations cover a range of latitudes extending from the southern to northern mid-latitude regions. One of these occultations occurs during the phasing orbit during the time period when the Sun-12irth-orbiter angle is less than 5 deg. The closest distance to Jupiter attained during any of the post-insertion orbit occultations is 2.2 million km, on the third orbit. The tour contains five passages through Jupiter's umbra (in addition to the one on the insertion orbit). One umbral pass occurs on the phasing orbit during the time period when the SLln-Karlh-orbiter angle is less than 5 deg.

One passage each through the wake of Europa and Ganymede is provided, and two arc provided through the wake of Callisto, all at altitudes of less than one satellite radius. Two Alfven wing passages are provided within one satellite radius of the surface at Ganymede, one at Europa, and two at Callisto. One additional passage through Ganymede's Alfven wing occurs during which the ol-biter passes within two radii of the surface.

The orbiter achieves an apojove distance of 143 Jupiter radii (RJ) on the tail petal orbit, less than the goal of 150 RJ set by the fields ancl particles science team. In spite of this shortfall, this tour was still deemed desirable by this team because the tail passage occurs after the eighth rather than the tenth flyby, and because another passage through the tail region is provided on the preceding orbit reaching an apojove of approximately 100 RJ.

The reduced apojove distance of 143 RJ is the result of an interesting interplay between the limitations of Callisto's ability to perform gravitational assist and the small but important gravitational effect of the Ganymede 9A nontargeted flyby. The Ganymede 9A nontargeted flyby (an inbound, lightside encounter) reduces period by about 3.5 dayS, so that in order to achieve the 83.4 day flight time between the Callisto 9 and 10 flybys in this tour, the Callisto 9 flyby must actually raise period to nearly 87 days. Thus, the Callisto 9 flyby altitude is lower in this tour than it would be if there were no Ganymede 9A flyby. A distance of 1 50 RJ at the tail petal apojove could be achieved by using the Callisto 9 targeted flyby to increase period approximately eight more clays, targeting to a Callisto 10 outbound flyby about half a Callisto rev later. In order to raise period an additional eight clays, the Callisto 9 flyby altitude would have to be lowered. As it happens, raising the period another eight clays would drive the Callisto 9 flyby altitude below the 200 km navigation-imposed lower limit unless 10-20 m/s of deterministic AV is added. However, if not for the extra c! ffort needed to counteract the slight period-redLlcill~ effect of the Ganymede 9A flyby, the Callisto 9 flyby could indeed raise period the required amou nt without going below the 200 km limit. In effect, this tour provides a nontargeted flyby with Ganymede, low deterministic AV, and an extra pass through the magnetotail at 100 RJ at the cost of I-educing the greatest distance attained in the magnetotail from 150 to 143 RJ.

initial optimization analysis of this tour showed that the deterministic AV cost to keep all four non-targeted flybys at less than 50,000 km altit ude (the highest altitude at which 1 -km SS1 resolution can be obtained) wo uld be about 33 m/s. Furth er analysis with the altit ude constraints relaxed showed that allowing the Ganymede 9A flyby altitude to increase to 80,000 km resulted in lower altitudes at Europa 3A and Callisto 8A and red uced th e AV cost to only 16 111/S. Thus the sacrifice of some globs] coverage of Ganymede act ually improved the Europa and Callisto coverage and cut the AV cost roughly in half.

A single opport unity to obtain a distant Io occultation occurs in this tour on orbit 6, at a distance of approximately 3.3 million km from Io. Six more such opportunities occur on orbit 9 (the tail petal orbit), at distances of 9.6 - 10.5 million km from 10. The Orbiter is C] OSCL' to Io on orbit 6 than on orbit 9 because the apoj ove is cl oser to the dawn terminator at this point in the tour [see also the "petal plot" of Figure 3). Small changes to the orbital inclination are necessary to accomplish these occultations. The changes arc made d uring the optimization process by constraining the flyby latitude of the targeted flyby preceding the occultations and re-optimizing the rest of the tour. Since the transfer from Callisto 9 to Callisto 10 is a resonance, the necessary slight change in inclination on orbit 9 can be accomplished without appreciable cost, To take advantage of the opportunity on orbit 6 however, inclination must be changed by about 0.3 deg. from the optimal value. This costs about 7 m/s extra deterministic AV, and necessitates a change of about 15 deg. in the latitude of the Europa 6 flyby. Since the opportunity on orbit 6 occurs closcr' to Io than the ones on orbit 9, it is likely to yield better results. The Galileo project chose to accept the extra 7 In/s cost of this opportunity ant] include it as part of the adopted tour, bringing the total AV up to 23 m/s, still low compared to other tours.

The total absorbed radiation during the tour is 123 Krad, less than the 150 Krad limit. Apojove of the tail petal mbit is reached on August 8, 1997 at a solar phase angle of 175 deg. and an inclination of 0.3 deg to Jupiter's equator. "l'he tour ends on November 11, 1997, 5 days after the last targeted flyby ancl 4 days after the nominal end-of-mission on November 7, 1997 (23 months after insertion into orbit about Jupiter).

EXTENDED MISSION IMPLICATIONS

The tour presented here contains only two flybys of Europa before the tail petal orbit. Neither of these provided an Alfven wing passage. A near-polar pass is necessary to satisfy this requirement, preferably at a low altitude. Since this requirement was not previously satisfied, the last flyby was designed to be a targeted encounter of Europa providing an Alfven wing passage. This flyby (Europa 11) also establishes a resonant orbit with Europa having a period of 43 days, leading to a re-encounter with Europa in January, 1998 for no deterministic AV cost. It is possible to choose aimpoints at the Europa 12 flyby which allow resonance with Europa to be maintained, allowing a Europa 13 flyby for no additional deterministic AV cost. One of these choices (a latitude of about 20 degrees and an altitude of 8,000-9,000 km) would yield very good high resolution NIMS coverage not available in the nominal tour. Resonance with Europa could be maintained indefinitely, allowing an unlimited number of subsequent Europa flybys for only the AV cost of navigation.

CONCLUSIONS

The tour selected by the Galileo project and presented here is the ultimate product of years of refinements in tour design techniques, as well as evolution in science requirements and mission constraints. The development and continuous improvement of these techniques has enabled the design of a tour yielding high science return while satisfying numerous constraints, including some imposed since launch. In particular, the low AV cost of this tour allowed the project to exercise the option of performing the Ida flyby while retaining a high level of science return in the tour.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to L.A. D'Amario, J.R. Johannesen, G. R. Garner. J. L. Pojman, J. M. Neff , and E.A. Rinderle, whose assistance throughout the tour design effort was invaluable.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

1. O'Neil, W. J., "Galileo Completing VEEGA - A Mid-Term Report," Paper IAF-92-0560, presented at the 43rd Congress of the International Astronautical Federation, August 28- September 5, 1992, Washington, D.C.

2. D'Amario, L. A., Bright, L. E., and Wolf, A. A., "Galileo Trajectory Design," *Space Science Reviews*, Vol. 60, New. 1-4, May, 1992, pp. 23-78,

3. Diehl, R.E., Kaplan, D.L., and Penzo, P. A., "Satellite Tour Design for the Galileo Mission," Paper AIM-83 -0101, presented at the AIM 2 1st Aerospace Sciences Meeting, January 10-13, 1983, Reno, NV.

4. Wolf, A. A., "A Generalized Strategy for Tour Design for the Galileo Mission," Paper AIAA-84-2015, presented at AIAA/AAS Astrodynamics Conference, August 20-22, 1984, Seattle , WA.

5. Longuski, J.M., and Wolf, A. A., "The Galileo orbital Tour for the 1986 Launch opportunity, " Paper AIAA-86-2006-CP, presented at the AIAA/AAS Astrodynamics Conference, August 18-20, 1986, Williamsburg, VA.

6. Uphoff, C., Roberts, P.H., and Friedman, L.D., "Orbit Design Concepts for Jupiter Orbiter Missions," Paper AIAA-74-781, presented at AAS/AIAA Astrodynamics Conference, June, 1979, Provincetown, MA.

7. Minovitch, M. A., "Gravity Thrust Jupiter Orbiter Trajectories Generated by Encountering the Galilean Satellites," Journal *of Spacecraft and Rockets,* Vol. 9, No. 109, October 1'372, pp. 751-756.

8. Niehoff, J. C., 'Touring the Galilean Satellites," *Journal of Spacecraft and Rockets,* Vol. 8, No. 10, October, 1971, pp. 1021-102,7.

9. D'Amario, L. A., Byrnes, D.V., Stanford, R.H., "A New Method for optimizing Multiple-Flyby Trajectories," *AIAA Journal of Guidance and Control,* Vol. 4, No. 6, November-December, 1981, p. 591.